HARMONIC ANALYSIS OF THE BIENNIAL ZONAL-WIND AND TEMPERATURE REGIMES

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ABSTRACT

Based upon 78 months of mean-monthly zonal-wind and temperature data, the phase angle and amplitude of the third (26-month) harmonic is determined as a function of latitude and height for stations within or bordering the North Pacific Ocean. In tropical latitudes the 26-month zonal-wind oscillation can always be traced down to the 200-mb. surface and frequently much lower. However, the 26-month temperature oscillation is usually not detectable below the 100-mb. level. In temperate latitudes, particularly at high levels, a mean-monthly zonal-wind oscillation of about 26-month period occurs which, with considerable justification, can be associated with the 26-month oscillation in the Tropics. Analysis of the 26-month temperature oscillation shows that this oscillation is even more easily traced into the temperate latitudes at high levels, but with a rather pronounced phase shift, so that north of the Tropic of Cancer the minimum temperature in the 26-month oscillation occurs at approximately the same time as the maximum temperature occurs south of this latitude. The thermal wind resulting from this temperature change with latitude is consistent with the observed 26-month zonal-wind oscillation.

A search for the cause of the heating and cooling with which the biennial wind oscillation apparently is associated is complicated by the fact that in tropical latitudes the downward progression of the warming with time appears most likely associated with small-scale eddy heat fluxes, while in polar and temperate latitudes the heating and cooling take place nearly instantaneously at all levels, suggesting the influence of vertical motions associated with a reversible meridional cell.

1. INTRODUCTION

In recent years meteorologists have become fascinated with the approximately biennial oscillation in the zonal wind so evident in the tropical stratosphere. The main features of this oscillation can be noted from figure 1, wherein are plotted 12-month running average mean-monthly zonal-wind components at Eniwetok for pressure surfaces of 30, 50, and 100 mb. It is seen that the amplitude of the oscillation tends to increase with height and that there is a phase shift with height such that the time of maximum east wind at 100 mb. tends to follow the time of maximum east wind at 30 mb. by nearly a year,

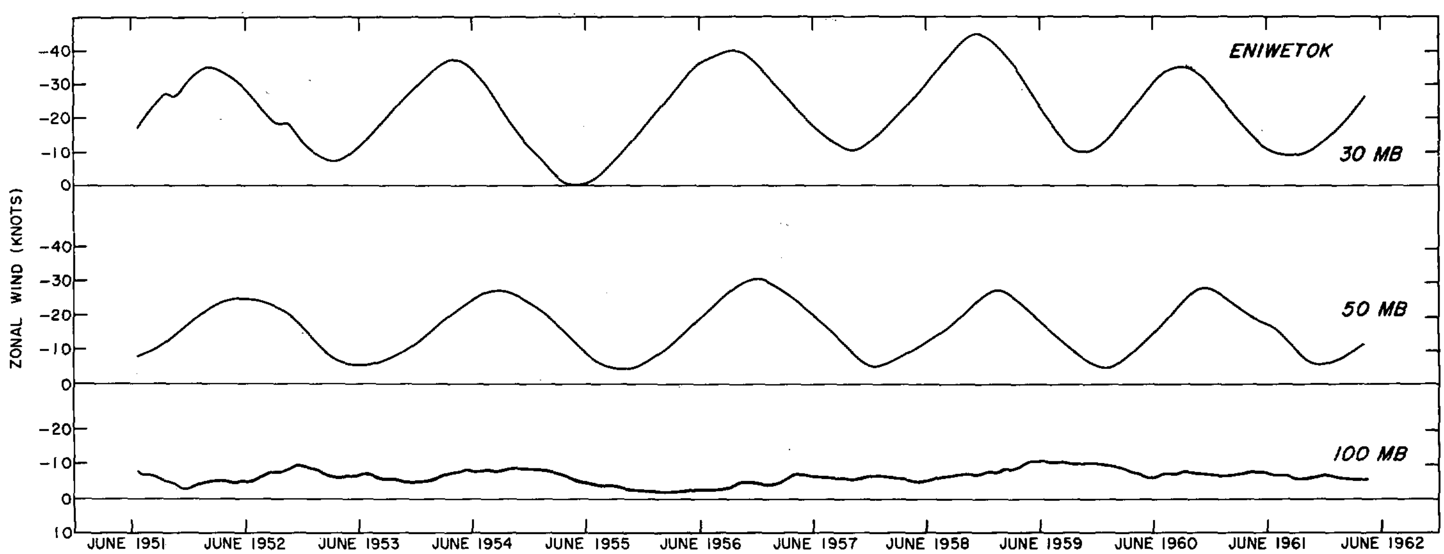

FIGURE 1.—Twelve-month running average mean-monthly zonal wind at Eniwetok at pressure surfaces of 30, 50, and 100 mb.

TABLE 1.—*Period of oscillation of the mean-monthly zonal wind at Eniwetok at 50 mb. (Based upon 12-month running averages)*

East wind maximum	East wind minimum	Half period (months)		Period (months)	Speed range (knots)
		Maximum to minimum	Minimum to maximum		
May 1952					
	May 1953	12			20
Aug. 1954			15	27	22
	Sept. 1955	13		28	23
Dec. 1956			15	28	26
	Dec. 1957	12		27	26
Jan. 1959			13	25	23
	Dec. 1959	11		24	23
Nov. 1960			11	22	23
	Nov. 1961	12		23	22
Average		12.0	13.5	25.5	23.1

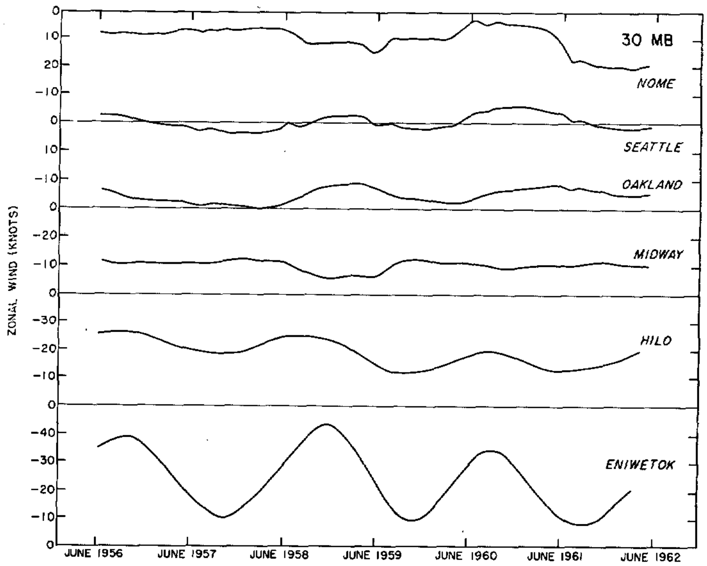

FIGURE 2.—Twelve-month running average mean-monthly zonal winds at 30 mb. at Nome, Seattle, Oakland, Midway, Hilo, and Eniwetok.

i.e., the oscillations at these two surfaces are almost out of phase. Table 1 shows the time intervals between individual east wind maxima and minima at Eniwetok at 50 mb., a surface sufficiently high in the atmosphere so as to show the true character of the oscillation and yet not so high as to sacrifice reliability due to sparseness of data. While over the 11-yr. period, the oscillation has an average period of 25.5 months, in recent years the period has become shorter. It should also be noted that the time from east wind maximum to east wind minimum averages 1.5 months less than the time from minimum to maximum, indicating an asymmetry in the oscillation. Nevertheless, the speed range has changed little during the 11-yr. interval and there is no sign that the oscillation is "running down".

In order to contribute to the further understanding of this rather surprising phenomenon, it is desirable to extend the scope of the analysis and consider whether this approximately biennial oscillation exists in the tropical troposphere and/or in the troposphere or stratosphere of temperate and polar latitudes. Veryard and Ebdon [1] found no firm evidence for the existence of the oscillation in the tropical troposphere. Angell and Korshover [2], on the other hand, showed some evidence for the extension of the oscillation into the stratosphere of the temperate latitudes. Thus, a plot of 12-month running averages of the mean-monthly zonal-wind component (which eliminates the annual variation in zonal wind but at the same time reduces the amplitude of any biennial oscillation), shows (fig. 2) that at 30 mb., particularly at Oakland and Seattle, there is evidence for a zonal-wind oscillation very nearly in phase with the zonal-wind oscillations noted at Eniwetok and Hilo. Recent high-level wind data obtained from Point Arguello indicate that the oscillations noted at Oakland and Seattle extend to at least 10 mb. The similarity of these oscillations for tropical and temperate latitude stations even extends to the time interval between east wind maxima, this interval being considerably longer between 1956 and 1958 than between 1958 and 1960. At Midway, however, there is very little variability in the 12-month running average of the mean-monthly zonal-wind, and what variability exists appears to be out of phase with the variability noted to the north and south. While the zonal-wind oscillation at Nome has some similarities to the oscillations at Seattle and Oakland, the period appears greater, thus leading to an out-of-phase relationship in January 1958 and an in-phase relationship in January 1961. On the basis of an analysis of the high-level winds at Berlin, Labitzke-Behr et al. [3] have also suggested that the period of oscillation is greater at northern latitudes.

Further analysis of the 12-month running average zonal wind at stations near 30° N. shows that while the amplitude of the 26-month oscillation is very small at 30 and 50 mb. at stations such as Midway, San Diego, and Santa Monica, at 100 mb. (and 200 and 300 mb. as well) the amplitude is relatively large (fig. 3). This feature extends westward across the Pacific, being even more evident at Marcus. Furthermore, as shown in figure 3, particularly at Santa Monica and San Diego these 100-mb. oscillations are generally in phase with the 50-mb. oscillations at Hilo and the 30-mb. oscillations at Oakland. Observations such as these serve to whet one's appetite and indicate the desirability of a rather thorough analysis of the 26-month oscillation with respect to latitude and height. That is the purpose of this paper, using upper-air stations within, or bordering upon, the North Pacific Ocean.

2. PROCEDURES

An objective analysis of the approximately 26-month oscillation requires a form of either spectral or harmonic analysis. With the possibility of a variation in period with either latitude or height, the most satisfying procedure would be a spectral analysis to obtain the period, followed by an appropriate harmonic analysis to delineate the

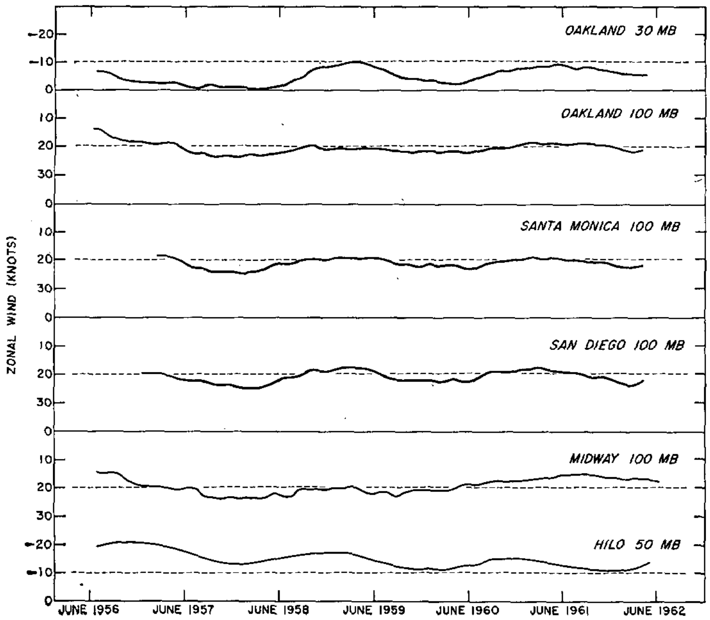

Figure 3.—Twelve-month running average mean-monthly zonal winds at various pressure surfaces at Oakland, Santa Monica, San Diego, Midway, and Hilo.

phase. Such a technique was beyond our resources and herein we have been forced to rely upon a simple harmonic analysis. Consequently if the period of oscillation does deviate considerably from 26 months, our phase angles may be in error.

It is apparent from table 1 that, as in the case of sunspot numbers, the period of oscillation of the mean-monthly zonal winds varies through the years. For purposes of phase comparison, then, it is essential that the harmonic analysis be based on the same years at all stations. Inasmuch as at most polar and temperate latitude stations reliable wind statistics at pressure surfaces such as 30 mb. have been obtained only since 1955, it is necessary to limit the harmonic analysis to the 7-yr. period 1956–1962 inclusive, even though at some tropical stations reliable upper-level winds were obtained many years earlier (see fig. 1). It should be emphasized that, except when the biennial oscillation is large, such a record length is rather short for a really accurate estimation of phase and amplitude.

Two alternate methods of harmonic analysis were considered. The first was to use unsmoothed mean-monthly zonal winds (and temperatures) for the 78-month period from March 1956 through August 1962 and calculate the third harmonic. One danger in this procedure is that in temperate latitudes, where the annual variation is large and the 26-month oscillation is weak, a phase bias may be introduced into the 26-month oscillation, particularly when the period of record begins in March and ends in August. The second procedure considered was to eliminate the annual variation by taking 12-month running averages, and to calculate the third harmonic

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Table 2.—*Date of minimum east wind (maximum west wind) as determined by harmonic analysis*

	Harmonic analysis (third harmonic) of 78 months of unsmoothed mean-monthly zonal winds	Harmonic analysis (third harmonic) of 72 months of mean-monthly zonal winds smoothed by finding 12-month running averages
Anchorage (300 mb.)	June 17, 1959	Aug. 24, 1959
Spokane (30 mb.)	Nov. 24, 1959	Dec. 15, 1959
(50 mb.)	Sept. 24, 1959	Nov. 12, 1959
Oakland (30 mb.)	Jan. 12, 1960	Feb. 9, 1960
(50 mb.)	Dec. 9, 1959	Feb. 18, 1959
(100 mb.)	Dec. 21, 1959	Nov. 12, 1959
Santa Monica (30 mb.)	Sept. 30, 1959	Dec. 15, 1959
(50 mb.)	Oct. 3, 1959	Dec. 3, 1959
San Diego (30 mb.)	Dec. 19, 1960	Oct. 9, 1960
Midway (25 mb.)	Apr. 19, 1959	Jan. 12, 1959
(200 mb.)	Aug. 9, 1959	July 12, 1959
Kwajalein (300 mb.)	June 18, 1960	June 3, 1960

from smoothed mean-monthly data extending from June 1956 to May 1962 inclusive. This technique has the disadvantage that the period of oscillation appears to be more nearly 26 months than 24 months, to which should be added the danger of throwing up false periodicities by averaging of data in which errors are present. Table 2 shows some dates of minimum east wind (or maximum west wind) as deduced from the two methods. Dates are average statistics for three full cycles of 24 or 26-month period and, logically, have been placed near the middle of the period of record. Comparison has been limited to cases where the 26-month oscillation is of small amplitude and consequently where the phase might be considered most doubtful. The average difference in phase is 1½ months with the maximum difference in phase about 3 months. There is some tendency for the phase to be later when the 12-month running average zonal wind is used. In the belief that the above difference in phase would not affect our results significantly, in this paper we applied the simpler procedure of taking the third harmonic of 78 months of unsmoothed mean-monthly data.

Another factor of some importance is the number of observations available for any given month. Obviously, the fewer the observations, the less reliable the monthly mean. For stations within the continental United States mean-monthly data are not presented in the summary forms unless there are at least 10 observations during the month, so that for these stations the limiting number of observations was more or less automatic. For many of the island stations in the North Pacific, however, data were obtained from the National Weather Records Center, and in these cases means were evaluated regardless of the number of observations during the month. At these stations, we arbitrarily decided to use the monthly mean values if five or more observations were available for the month.

TABLE 3.—*Number of months for which monthly-mean wind and temperature data were not available between March 1956 and August 1962*

	Latitude ° ′	Longitude ° ′	25 (30) mb. Temp.	25 (30) mb. Wind	50 mb. Temp.	50 mb. Wind	100 mb. Temp.	100 mb. Wind	200 mb. Temp.	200 mb. Wind	300 mb. Temp. Wind	500 mb. Temp. Wind	700 mb. Temp. Wind
Barrow	71 18 N.	156 47 W.	7	22	1	10	1	7	1	4	2	1	1
Kotzebue	66 52 N.	162 38 W.	4	22	0	13	0	4	0	0	0	0	0
Nome	64 30 N.	165 26 W.	1	12	0	3	0	2	0	0	0	0	0
Anchorage	61 10 N.	149 59 W.	4	17	0	6	0	4	0	1	0	0	0
St. Paul Island	57 09 N.	170 13 W.	9	26	5	13	4	11	1	5	4	1	1
Cold Bay	55 12 N.	162 43 W.	0	25	0	17	0	11	0	8	2	0	0
Seattle	47 27 N.	122 18 W.	6	10	4	6	4	4	4	4	4	4	5
Salem	44 55 N.	123 01 W.	3	11	3	3	3	3	3	3	3	3	3
Oakland	37 44 N.	122 12 W.	1	1	0	0	0	0	0	0	0	0	0
[Santa Maria Pt. Arguello]	34 40 N.	120 35 W.	0	20	0	11	0	11	2	6	2	2	3
Santa Monica	34 01 N.	118 27 W.	6	6	6	6	4	4	1	1	1	1	1
San Diego	32 49 N.	117 08 W.	3	5	3	5	4	4	3	4	4	4	4
Midway	28 13 N.	177 22 W.	17	12	13	7	9	4	3	0	1	0	0
Lihue	21 59 N.	159 21 W.	3	2	0	2	0	3	0	0	0	0	0
Hilo	19 43 N.	155 04 W.	0	4	0	3	0	0	0	0	0	0	0
Wake	19 17 N.	166 39 E.	0	0	0	0	0	0	0	0	0	0	0
San Juan	18 26 N.	66 00 W.	1	6	1	2	1	2	1	2	2	2	3
Johnston	16 44 N.	169 31 W.	7	9	6	7	9	9	9	7	7	7	7
Guam	13 33 N.	144 50 E.	0	0	0	0	0	0	0	0	0	0	0
Eniwetok	11 21 N.	162 21 E.	2	2	2	2	2	2	2	2	2	2	2
Kwajalein	8 43 N.	167 44 E.	20	22	9	10	4	5	4	5	5	5	5
Majuro	7 05 N.	171 23 E.	7	7	4	4	4	4	4	4	4	4	4
Canton	2 46 S.	171 43 W.	0	0	0	0	0	0	0	0	0	0	0

When no monthly mean was calculated owing to sparsity of observations, use was made of the average value for this same month as evaluated from the remainder of the data. Of course, this yields a very conservative estimate, and the amplitude of the oscillations is reduced through such a procedure. At some stations, at the higher levels, the decrease in amplitude with height is believed due to this technique, and indeed, the necessity of more and more interpolation the higher one goes in the atmosphere makes it difficult to decide whether the amplitude of the 26-month oscillation is still increasing at heights above 80,000 ft. The number of months for which monthly mean wind and temperature data were interpolated is shown in table 3. Also indicated in this table is the latitude and longitude of the stations to be utilized.

The plan, then, is to make a harmonic analysis of the mean-monthly zonal wind and mean-monthly temperature at pressure surfaces of 25 (30), 50, 100, 200, 300, 500, and 700 mb., utilizing upper-air stations in the central North Pacific, along the west coast of the contiguous United States, and in Alaska. In this way one can obtain fairly reliable wind and temperature data over the latitude range from Canton Island (3° S.) to Barrow, Alaska (71° N.). However, since there is considerable longitude variation within the above group of stations, it was necessary to make sure that the 26-month oscillation does not vary with longitude. Table 4 shows the time of minimum east wind (maximum west wind) at Wake, Hilo, and San Juan, stations varying in latitude by little more than a degree, yet varying in longitude by nearly 130°. There is no evidence from table 4 of a significant phase shift with longitude and consquently it is assumed that the longitudinal variation of the upper-air stations has no effect upon the results presented herein.

TABLE 4.—*Date of minimum east wind (maximum west wind) at tropical stations varying in longitude but at approximately the same latitude*

	30 mb.	50 mb.	100 mb.
Wake (166° E.)	Aug. 19, 1959	Nov. 27, 1959	Jan. 21, 1960
Hilo (155° W.)	Sept. 4, 1959	Nov. 30, 1959	Feb. 3, 1960
San Juan (66° W.)	Sept. 12, 1959	Nov. 30, 1959	Jan. 26, 1960

3. VERTICAL PROPAGATION OF THE 26-MONTH ZONAL-WIND OSCILLATION

Figure 4 shows, for the 26-month harmonic, the date of minimum east wind (maximum west wind) as a function of pressure for various tropical stations. It is again emphasized that this date is an average statistic for three full 26-month cycles and the years 1959–60 were utilized only because it appeared logical to make use of dates near the center of the data records. The data are plotted on semi-log paper in order that the ordinate be proportional to height. Continuity in the date of minimum east wind (maximum west wind) is generally observable to 200 mb. and to even lower heights at stations such as Majuro, Hilo, and Midway. Very often, however, there is a tendency for the oscillation to shift to earlier dates at the lower levels. Because of the very small amplitude of the oscillation at these lower heights, the reality of this tendency is doubtful.

There is considerable evidence from figure 4 that the 26-month mean-monthly zonal-wind oscillation progresses downward more slowly near the equator than at higher latitudes and more slowly in the stratosphere than in the troposphere. This is confirmed in figure 5, where we have plotted the rate of descent of the oscillation (in meters per day) as a function of pressure interval and latitude. Between 25 and 50 mb. the average rate of descent is about 35 meters per day (a vertical velocity of only -0.04 cm. sec.$^{-1}$, incidentally), between 50 and 100 mb. about 50 meters per day, and between 100 and 200 mb. (generally in the troposphere at these latitudes) about 100 meters per day. Thus the rate of descent is at least twice as great in the troposphere as in the stratosphere. Within these pressure surfaces there is quite a pronounced

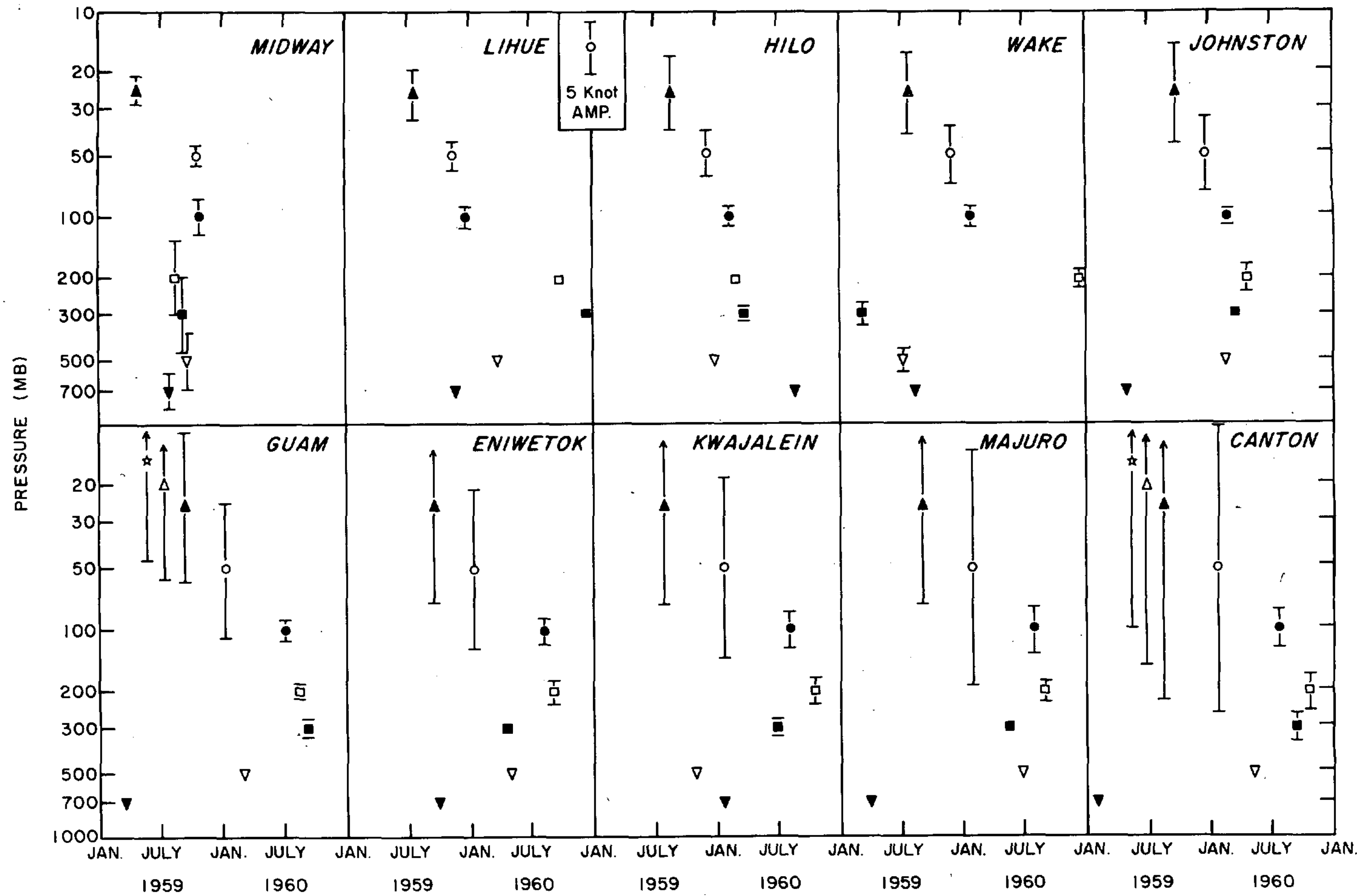

Figure 4.—Date of minimum east wind (maximum west wind) for the 26-month zonal-wind oscillation as a function of pressure (logarithmic scale) for tropical stations. Dates represent average statistic for three full 26-month cycles. The amplitude of the oscillation is indicated by the length of the vertical bar (see insert for scale). Vertical bar omitted when amplitude less than 1 kt.

tendency for the oscillation to propagate downward more rapidly as latitude increases. For example, between 25 and 100 mb. the rate of descent varies from about 25 meters per day in equatorial regions to about 60 meters per day at the Tropic of Cancer.

Figure 6 shows, for the 26-month harmonic, the date of minimum east wind (maximum west wind) as a function of pressure for stations in temperate and polar latitudes. Note that San Diego and Santa Monica continue to indicate a downward progression of the oscillation with time between 50 and 200 mb., but at the relatively great rate of about 100 meters per day (still a vertical velocity of only about -0.1 cm. sec.$^{-1}$). At the remainder of the temperate and polar-latitude stations the east wind minimum (west wind maximum) occurs at practically the same date at all elevations, with the possible exception of Salem, Seattle, and St. Paul Island where there is evidence for an upward propagation in the 100–25-mb. layer. Except for the evidence that the rate of downward propa-

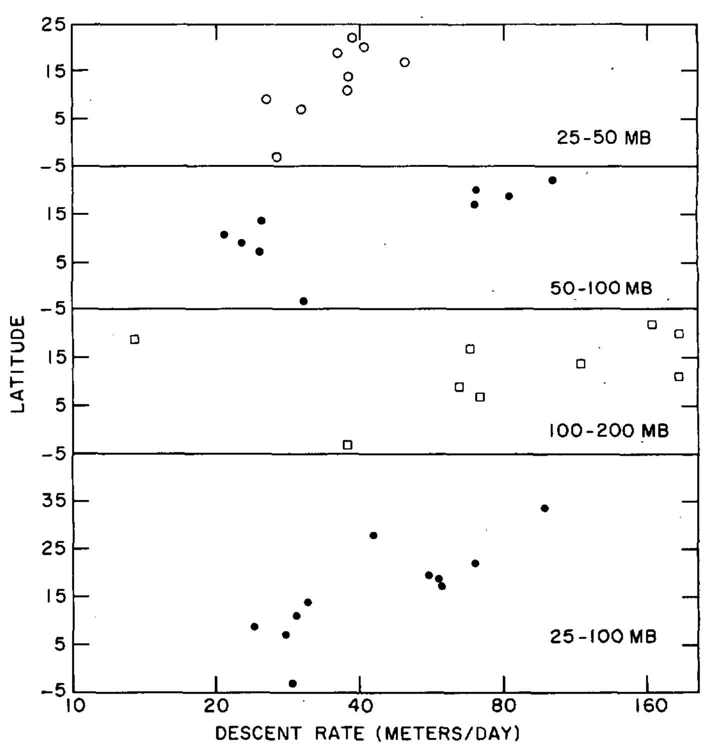

Figure 5.—Rate of descent of 26-month zonal-wind oscillation (meters per day) as a function of pressure intervals and latitude.

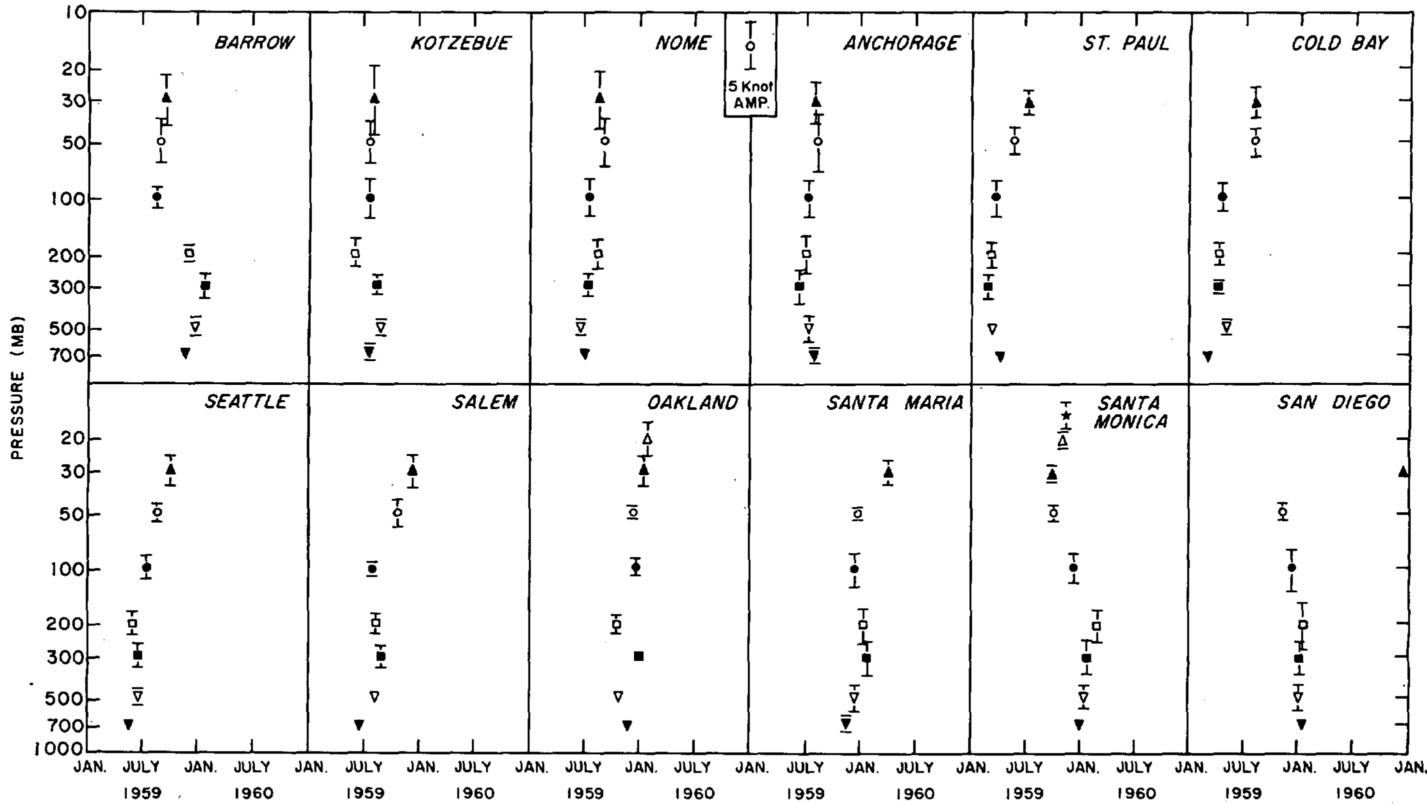

FIGURE 6.—Same as figure 4, but for polar and temperate-latitude stations.

gation does increase as latitude increases, one would be very doubtful about the reality of these 26-month zonal-wind oscillations in northerly latitudes, or at least doubt the justification of associating them with the 26-month oscillations of tropical latitudes. As we shall see, however, the temperature analysis indicates there is a basis for such an association.

4. LATITUDINAL VARIATION OF THE 26-MONTH ZONAL-WIND OSCILLATIONS

Figure 7 shows the variation of the date of east wind minimum (west wind maximum) with latitude at the various pressure surfaces. Because of the above-noted tendency for the east wind minimum (west wind maximum) to occur nearly simultaneously at all elevations in temperate and polar latitudes, while in equatorial latitudes there is a slow downward progression of the east wind minimum, at all heights below the 30-mb. surface the oscillation appears to occur earlier at the more northerly latitudes. An exception is 700 mb. where the picture is very chaotic. At 30 mb. the oscillation occurs at nearly the same time at all latitudes but with a pronounced minimum in amplitude near 30° N. The sparse data at 15 and 20 mb. suggest that at these surfaces the oscillation occurs earlier in equatorial latitudes. Particularly at 50 and 100 mb. there is a tendency for the oscillation to occur a little later at stations from Oakland to San Diego than one could expect from the overall trend. At first it was believed this was due to a bias in the harmonic analysis procedure, and for this reason harmonic analysis was also performed on the 12-month running average mean-monthly zonal winds at some of these stations (see table 2). However, a glance at table 2 shows that the discrepancy was not reduced by this alternate procedure.

One additional feature worthy of note in figure 7 is the tendency, especially at the lower levels, for the oscillation to occur earlier at about 60° N. than at more poleward latitudes. There is a possibility that this trend is not real but is a result of a lengthening of the period of oscillation at these latitudes.

It is desirable to show the variation with latitude of the amplitude of the 26-month mean-monthly zonal wind since, if the wind variation is associated with some heating effect which uniformly tilts the isobaric surfaces, the amplitude of the oscillation might be expected to vary inversely as the sine of the latitude (geostrophic wind equation). Figure 8 shows that while there might be such a tendency at 100 mb., at 50 and 25 mb. the amplitude appears to vary nearly linearly with latitude, at least at latitudes between 20° N. and 5° N. These results are in fair agreement with those presented by Reed and Rogers [4] (see their fig. 3). It would appear that more is involved than the uniform tilting of isobaric surfaces, and this is confirmed by the temperature analysis.

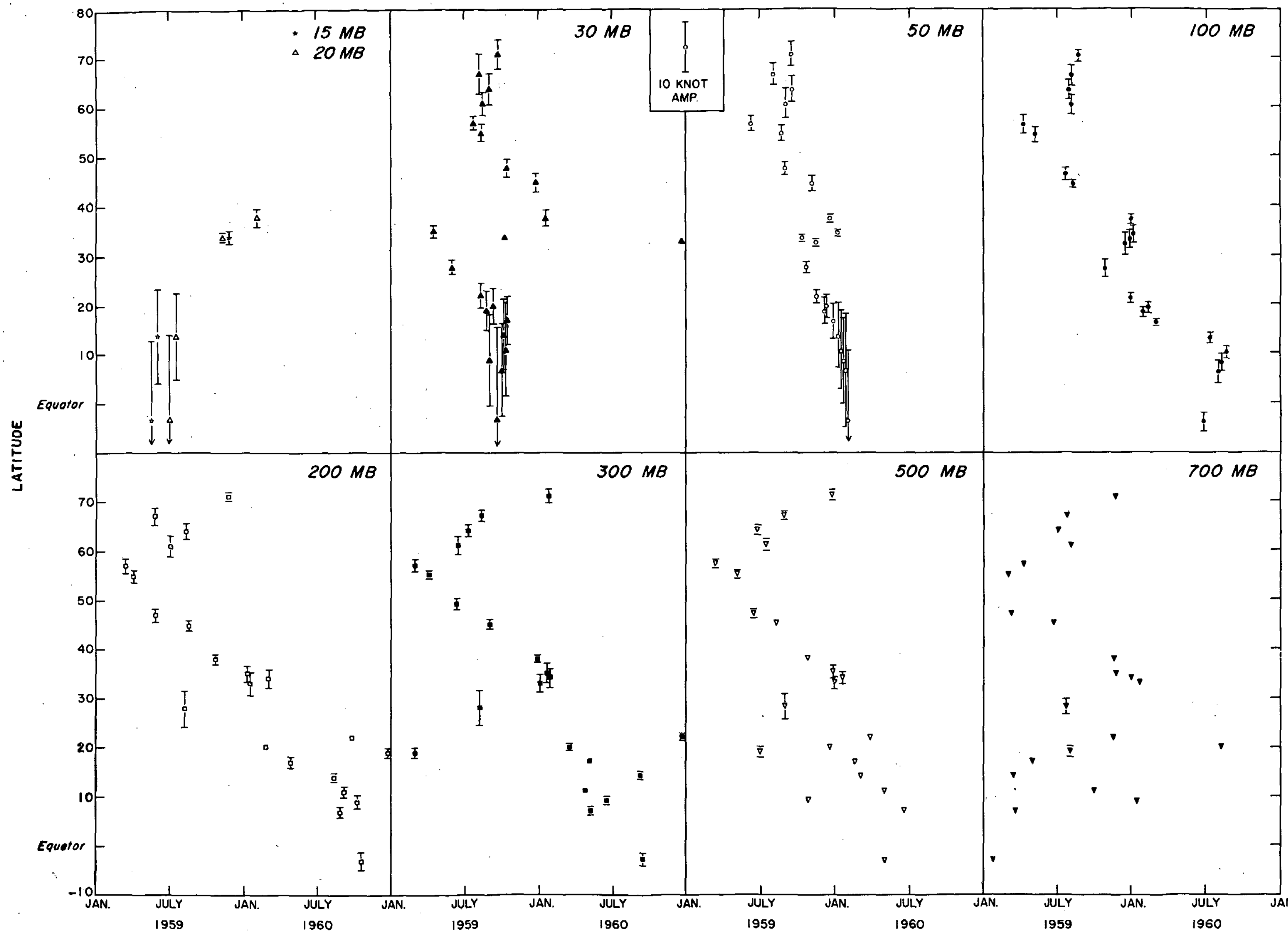

FIGURE 7.—Variation with latitude of the date of minimum east wind (maximum west wind) for the 26-month zonal-wind oscillation for various pressure surfaces. Otherwise, please see legend for figure 4.

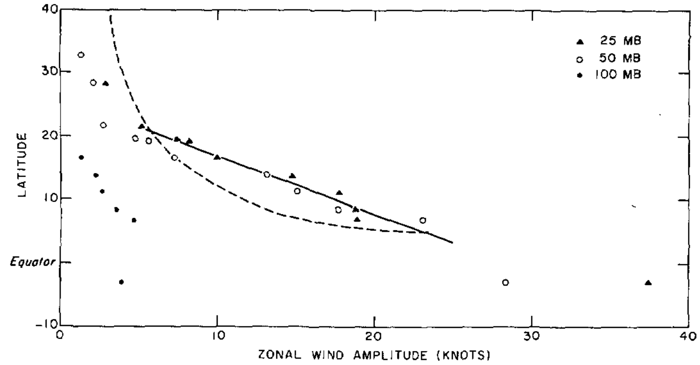

FIGURE 8.—Amplitude of 26-month zonal-wind oscillation as a function of latitude at pressures of 25, 50, and 100 mb. The dashed line indicates amplitude varying inversely as the sine of the latitude, the solid line an inverse linear relation.

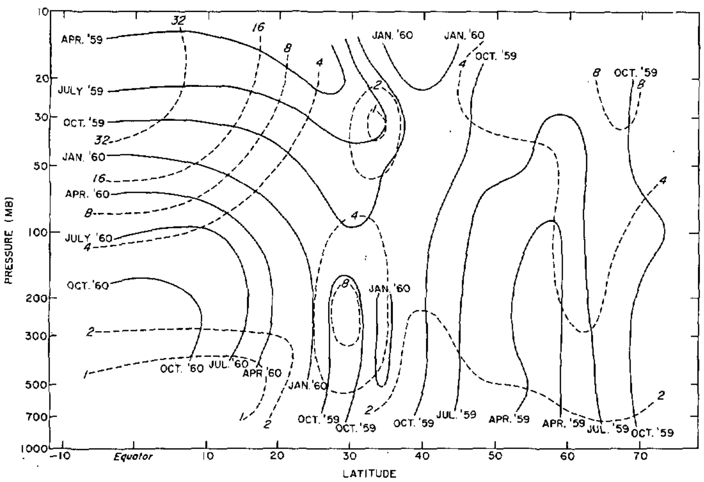

FIGURE 9.—Date of minimum east wind (maximum west wind) for the 26-month zonal-wind oscillation as a function of latitude and height (solid lines), and the amplitude thereof in knots (dashed lines). Dates represent average statistic for three full 26-month cycles.

5. THE 26-MONTH ZONAL-WIND OSCILLATION IN THE MERIDIONAL PLANE

Combining the features noted in figures 4, 6, and 7, we obtain figure 9, a meridional cross section showing the date of minimum east wind (maximum west wind) for the 26-month zonal-wind oscillation, and the amplitude of this oscillation. In connection with this figure we reemphasize that, owing to the small amplitude of the biennial oscillation north of 20° N. and the length of the period of record, the results in temperate and polar latitudes must be considered tentative. With regard to the amplitude, especially to be noted are the secondary maxima of 8 kt. at 30 mb. at 70° N. and at 200 mb. at 30° N., the latter situated beneath an area of minimum amplitude. With regard to the date of east wind minimum (west wind maximum), note that the slow downward progression of the oscillation in equatorial latitudes gives way to a quite rapid downward propagation near 30° N. Furthermore, there is the curiosity that in the troposphere and stratosphere at 55° N. the phase of the oscillation is similar to that found at 10 and 15 mb. in the Tropics.

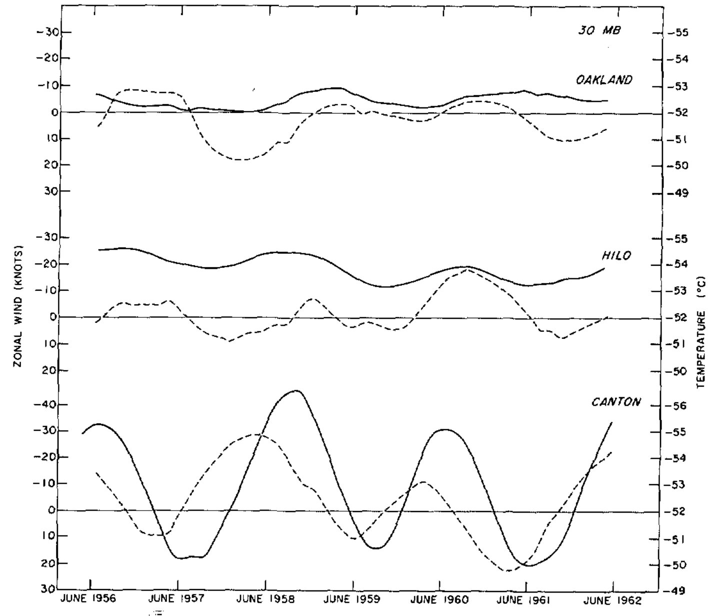

FIGURE 10.—Twelve-month running average mean-monthly zonal wind (solid line) and temperature (dashed line) at Oakland, Hilo, and Canton at 30 mb.

6. THE 26-MONTH TEMPERATURE OSCILLATION

Figure 10 shows 12-month running average mean-monthly temperatures at 30 mb. for Canton, Hilo, and Oakland (dashed lines). Please note that in this figure the temperature decreases upward. For comparison we also indicate the 12-month running average mean-monthly zonal winds (solid lines) for the same stations. It is seen that while there is a slight tendency for the time of minimum east wind (maximum west wind) to occur later with increasing latitude, the tendency is very pronounced in the case of the temperature oscillation, with nearly a 180° phase shift between equator and temperate latitudes. In other words, at the equator the temperature maximum precedes the east wind minimum by a few months while in temperate latitudes the temperature maximum tends to follow the east wind minimum by a few months.

One immediately senses the possibility that this temperature phase-shift with latitude leads to a temperature gradient with latitude, and that the thermal wind resulting from this temperature gradient is associated with the 26-month zonal-wind oscillation. As partial evidence that this is indeed the case, figure 11 shows the 12-month running average temperature difference between Canton and Oakland at 30 mb. plotted as a function of time.

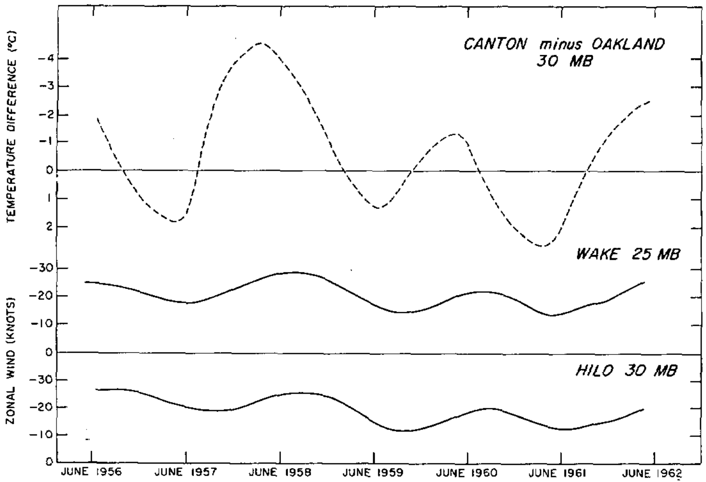

FIGURE 11.—Twelve-month running average mean-monthly temperature difference between Canton and Oakland at 30 mb. (dashed line) and 12-month running average mean-monthly zonal wind at Hilo at 30 mb. and at Wake at 25 mb. (solid lines).

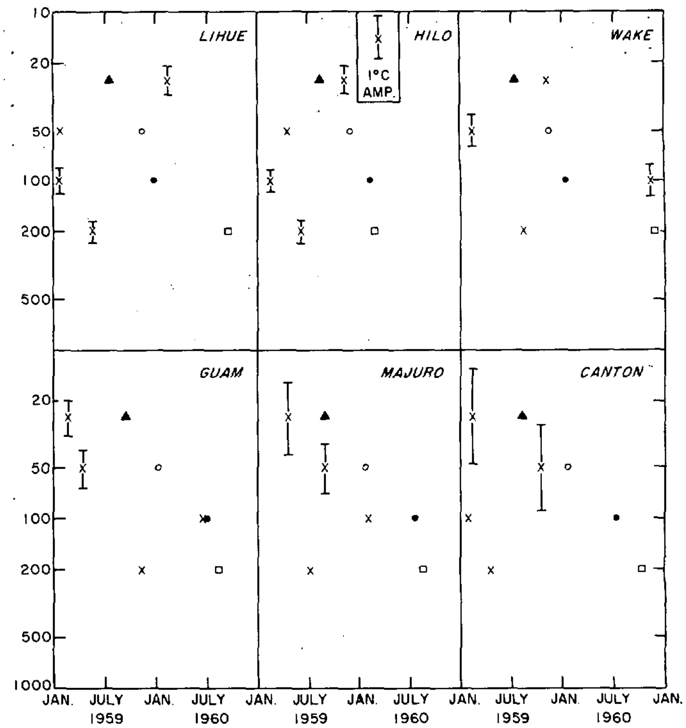

FIGURE 12.—Date of maximum temperature for the 26-month temperature oscillation as a function of pressure (logarithmic scale) for tropical stations. Dates represent average statistic for three full 26-month cycles. The amplitude of the oscillation is indicated by the length of the vertical bar (see insert for scale). Vertical bar omitted when amplitude less than 0.5° C. For comparison, times (but not amplitudes) of minimum east wind (maximum west wind) have been entered from figure 4.

Also plotted are the 12-month running average zonal winds at 30 mb. at Hilo and at 25 mb. at Wake, stations approximately half way (in latitude) between Oakland and Canton. It is seen that already at 25 mb. the wind and temperature-difference fluctuations are not too far out of phase; i.e., the winds tend to be more westerly when the temperature gradient shows a lower temperature to the north. From the change in time of minimum east wind with height at the very high levels (fig. 4), one would estimate that at about 15 mb. the time of west wind maximum, or east wind minimum, should coincide with the time when the 30 mb. temperatures at Oakland are lowest relative to the 30 mb. temperatures at Canton.

It is of interest to estimate the magnitude of the wind shear in the vertical obtained by substituting the average amplitude of the temperature difference in figure 11 (3°C.) in the thermal wind equation. One obtains thereby a shear of 6 kt. per 4400 m. Consequently, if one assumes practically no latitudinal temperature gradient at 100 mb. due to a 26-month temperature oscillation, which from later work appears reasonable, and furthermore assumes a linear increase in latitudinal temperature gradient up to the value indicated at 30 mb. between Canton and Oakland, then one would anticipate at 25 or 30 mb. a 6-kt. amplitude in the 26-month zonal-wind oscillation. The amplitude observed at Hilo and Wake is 7 and 8 kt., respectively, so that the hypothesis that the 26-month zonal-wind oscillation is associated with the thermal wind resulting from a phase shift with latitude of the 26-month temperature oscillation appears reasonable. As we did in the case of the 26-month zonal-wind oscillation, let us now take a more detailed look at the 26-month temperature oscillation using harmonic analysis.

7. VERTICAL PROPAGATION OF THE 26-MONTH TEMPERATURE OSCILLATION

Figure 12 shows, for the 26-month harmonic, the date of maximum temperature as a function of pressure for various tropical stations. As previously, the vertical bar through the time of maximum temperature indicates the amplitude of the 26-month temperature oscillation. For comparison, the date of minimum east wind (maximum west wind) has been copied from figure 4, but so as not to complicate the diagram unduly, the amplitude of the wind oscillation has been omitted. As is well known, at tropical stations at high levels (for the 26-month oscillation) the time of maximum temperature precedes the time of minimum east wind (maximum west wind) by a few months. It is also apparent, however, that, because of very small amplitudes, the time of maximum temperature does not possess the continuity in the vertical that the time of minimum east wind possesses. Only Majuro shows a good trend to as high a pressure as 100 mb. Because of this, despite the original plan, it was not deemed worthwhile to subject temperatures at tropospheric levels to harmonic analysis, as was done with the wind.

It is seen from figure 12 that, in agreement with the

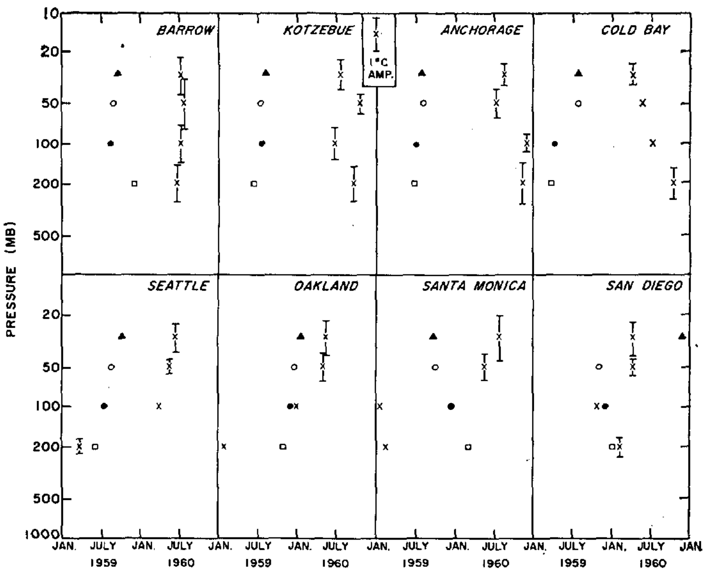

Figure 13.—Same as figure 12, but for polar and temperate-latitude stations.

26-month zonal-wind oscillation, there is evidence for an increase in the rate of descent of the 26-month temperature oscillation as the latitude increases (compare Guam and Canton). Furthermore, at Canton the 26-month temperature oscillation progresses downward more slowly than the wind oscillation, whereas at Majuro the rate of descent is practically the same, and at Guam the temperature oscillation descends more rapidly. Note that at Wake, Hilo, and Lihue the time of temperature maximum at the various pressure surfaces is quite chaotic, though the time of minimum east wind has good continuity. Thus, although the temperature may be the primary element in the 26-month oscillation, it is not so easily studied as is the wind, even though, in general, temperature observations are more numerous than wind observations at any given level.

Figure 13 shows for the 26-month harmonic the date of maximum temperature (and for comparison the date of minimum east wind) as a function of pressure at polar and temperate-latitude stations. As in the case of the 26-month zonal-wind oscillation, the temperature oscillation tends to be in phase at all heights, with the temperature oscillation surprisingly large at 100 and 200 mb. in polar latitudes.

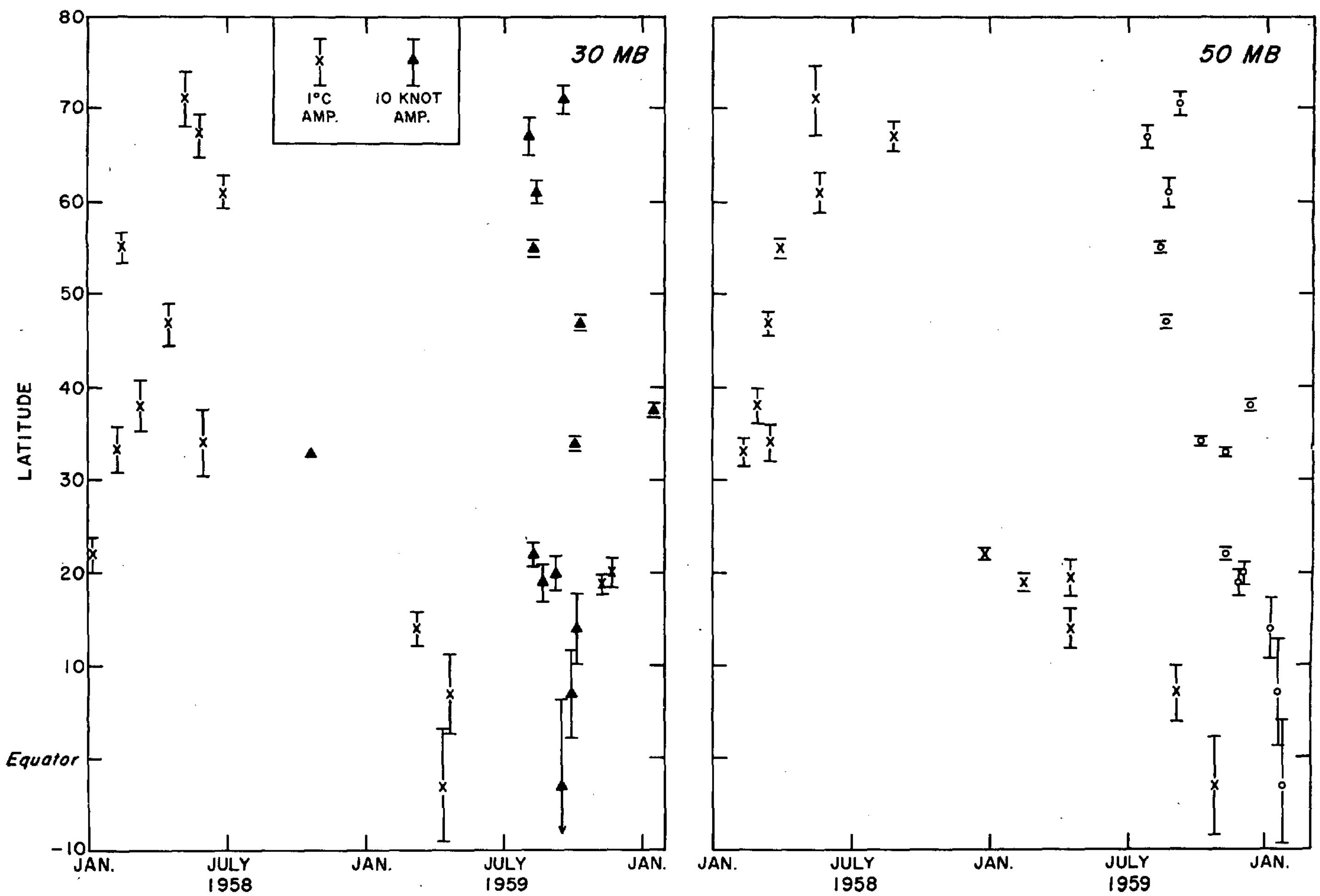

Figure 14.—Variation with latitude of the date of maximum temperature (crosses) and maximum west wind (from fig. 7) for the 26-month temperature oscillation at pressure surfaces of 30 and 50 mb. Otherwise, please see legend for figure 12.

8. LATITUDINAL VARIATION OF THE 26-MONTH TEMPERATURE OSCILLATIONS

Figure 14 indicates the variation with latitude of the date of maximum temperature at pressure surfaces of 30 and 50 mb., the only surfaces where the 26-month temperature oscillation is of sufficient amplitude to yield a reliable trend. At 30 mb. at the tropical stations the time of temperature maximum consistently precedes the time of east wind minimum (west wind maximum) by about 6 months. However, at 50 mb. the difference ranges from about 3 months at the equator to 9 months at the Tropic of Cancer. Apparently, the change with latitude of the rate of descent of the temperature oscillation is more rapid than that of the wind oscillation.

Certainly the most striking feature in figure 14, however, is the sudden change in date of temperature maximum which occurs near the Tropic of Cancer. It must be remembered that all the dates indicated in figure 14 could be changed by 26 months. Thus, in agreement with the latitudinal variation in the time of maximum temperature noted in figure 10, it is likely that the temperature maxima indicated between January and July 1958 in figure 14, actually belong between March and September 1960. In any event, as noted in figure 10, north of the Tropic of Cancer the 26-month temperature harmonic tends to be out of phase with the harmonic south of this latitude. We mentioned previously that this phase shift appears to be associated with the 26-month wind oscillation. Thus, figure 15 shows the time of maximum (+) and minimum (—) temperature (amplitude of harmonic in °C. also indicated) of the 26-month oscillation in the 25–50-mb. layer as obtained by averaging the times of maximum and minimum temperatures at the 25- and 50-mb. surfaces. With this layer relatively the coldest to the north and the warmest to the south in the months of May and June 1959, the thermal wind equation would lead us to expect a west wind maximum at 30 mb. at about this same time. Actually, we see from figure 7 that the 26-month zonal-wind oscillation had a maximum westerly component in August 1959. This agreement is sufficiently close so that one senses that, basically, the thermal wind equation is being obeyed, as previously suggested by us in this paper and as shown by Reed [5] for tropical latitudes.

The fact that in polar latitudes the 26-month temperature oscillation is quite pronounced at least as far as the 200-mb. surface (fig. 13) gives a reason for the existence of an east wind minimum (west wind maximum) in northerly latitudes as early as April 1959 (fig. 9). Thus, even though a warming trend is not obvious in the tropical troposphere, the presence of relatively low temperatures at all levels in the polar region during May and June 1959, would, through the thermal wind equation, be associated with a west wind maximum at about that time.

Finally, in figure 16 we indicate the amplitude of the 26-month temperature oscillation at 25 and 50 mb. as a function of latitude. As far as can be determined, the

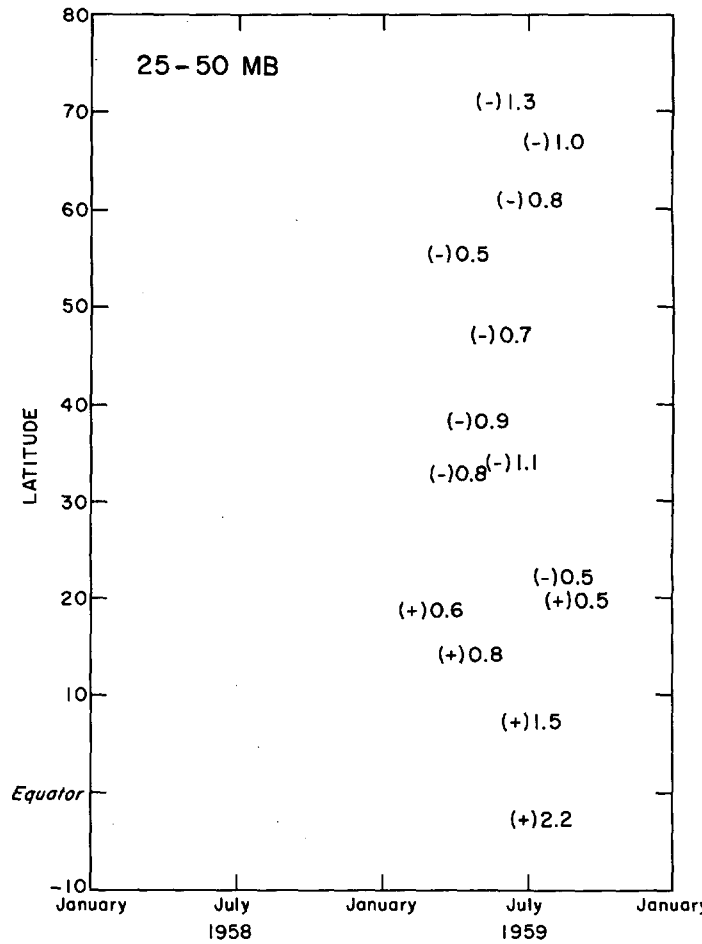

Figure 15.—Date of minimum temperature (—) and maximum temperature (+) for the 26-month temperature harmonic in 25–50-mb. layer. Average harmonic amplitude (°C.) also indicated. Dates represent average statistic for three full 26-month cycles.

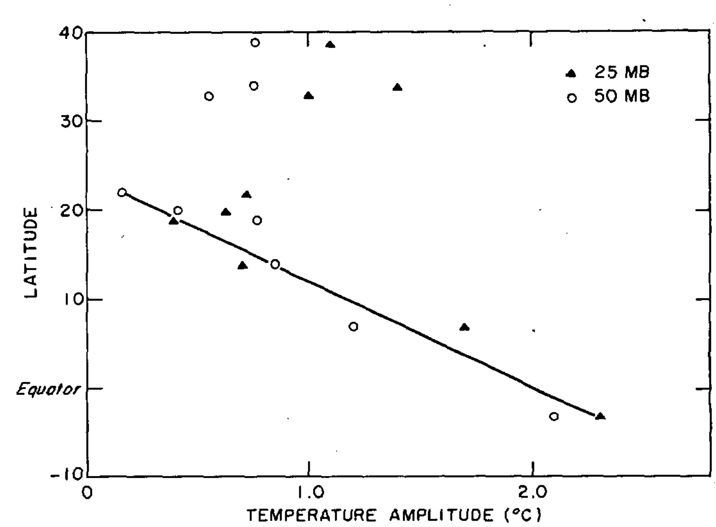

Figure 16.—Amplitude of 26-month temperature oscillation as a function of latitude at pressure surfaces of 25 and 50 mb. The solid line indicates an inverse linear relation.

amplitude decreases linearly with increasing latitude to the point of minimum amplitude near 20° N. The reason this approximately linear temperature-amplitude variation does not result in a 26-month zonal-wind amplitude which varies inversely as the sine of the latitude (geostrophic wind equation) may be due to the phase variation of the temperature oscillation with latitude.

9. DISCUSSION

One of the interesting bits of information culled from the above analysis is the tendency, in tropical latitudes, for the 26-month zonal-wind oscillation (and, presumably, the 26-month temperature oscillation) to descend more rapidly in the troposphere than in the stratosphere and more rapidly with increasing latitude in the stratosphere. This strongly suggests that the rate of descent increases as the atmospheric stability decreases, and this in turn suggests that the warming at successively lower levels in the Tropics is due to an eddy flux of heat. In temperate and polar latitudes, however, the 26-month wind and temperature oscillations appear almost independent of height, and it would seem most logical that these simultaneous temperature changes at all levels are produced by the ascent or descent of a whole column of air. Furthermore, the existence near the Tropic of Cancer of a rapid change in the time of maximum temperature derived from the 26-month temperature oscillation suggests the presence of a reversible meridional cell centered at this latitude. Such a meridional cell, operating for unknown reasons with a 24- or 26-month period, would cause temperatures in northerly latitudes to fall as a result of upward air motion at the same time that temperatures in southerly latitudes would rise as a result of descending motion. One might also consider the possibility of a non-reversible meridional cell which varies in strength and which allows diabatic influences to predominate when the cell is weak. In either case there is the difficulty that thereby one would expect temperature changes to occur nearly simultaneously at all elevations in the Tropics, which is not observed.

The dilemma, then, is that the temperature changes in tropical latitudes appear best explained by eddy heat flux whereas the temperature changes in temperate and polar latitudes appear best explained by large-scale vertical motions. One of the things that must be determined with more reliable data is whether the phase shift with latitude of the 26-month running average mean-monthly temperature is gradual, or whether it occurs abruptly at or near the Tropic of Cancer. Confirmation of one or the other of these alternatives would indicate whether the origin of the whole biennial oscillation lies in the high equatorial stratosphere, or whether there is no origin in the usual sense but simply an oscillation associated with a meridional cell.

On the basis of this analysis we dare not hazard a guess as to the cause of the biennial wind and temperature oscillations. While an extraterrestrial source for the oscillation is appealing in the sense that it tends to remove the problem from the domain of the meteorologist, the authors believe that one should not give up too easily the concept that the approximately biennial oscillation is associated with some resonant oscillation in the atmosphere.

10. CONCLUSION

Considerable evidence has been presented that the 26-month zonal-wind oscillation can be traced into the tropical troposphere and into the polar stratosphere and troposphere; in fact, that there is a hemisphere-wide reaction to the thermal pulse apparently originating in the high equatorial stratosphere. The 26-month wind oscillation appears to be related, through the thermal wind equation, with the 26-month temperature oscillation, but the wind oscillation is the more easily detected. While this analysis has unearthed some interesting possibilities as to the cause of the oscillation, the authors have not found one simple explanation which explains all the data.

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REFERENCES

1. R. G. Veryard and R. A. Ebdon, "Fluctuations in Tropical Stratospheric Winds," *Meteorological Magazine*, vol. 90, No. 1066, May 1961, pp 125–143.
2. J. K. Angell and J. Korshover, "The Biennial Wind and Temperature Oscillations of the Equatorial Stratosphere and Their Possible Extension to Higher Latitudes," *Monthly Weather Review*, vol. 90, No. 4, Apr. 1962, pp 127–132.
3. K. Labitzke-Behr et al., "The Yearly Changes of Stratospheric Circulation," *Meteorologische Abhandlungen*, Band XX, Heft 2., Aug. 1961, 58 pp.
4. R. J. Reed and D. G. Rogers, "The Circulation of the Tropical Stratosphere in the Years 1954–1960," *Journal of the Atmospheric Sciences*, vol. 19, No. 2, Mar. 1962, pp 127–135.
5. R. J. Reed, "Evidence of Geostrophic Motion in the Equatorial Stratosphere," *Quarterly Journal of the Royal Meteorological Society*, vol. 88, No. 377, July 1962, pp 324–327.